COMPLEX ASSESSMENT OF HAZARDOUS EFFECTS OF IMPACTS OF COSMIC OBJECTS.

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Introduction: Over the past decades, an adequate understanding of impact processes and their consequences has been achieved, and several complex models of individual impact events have been developed (Tunguska, Shoemaker-Levy 9, Chelyabinsk). However, in general, assessments of hazardous effects (shock waves, radiation, fires, seismic waves, ionospheric perturbations) are mainly based on the analogy between impacts and explosions [1]. The main goal of our work is to develop a model / method / algorithm for reliable estimates of hazardous effects and impact consequences over a wide range of impactor parameters. We modeled the impacts of stony and icy bodies ranging in size from 30 m to 3 km entering the atmosphere with various speeds at angles from 15° to 90°.

Method: Simulations of impacts were carried out by numerical solution of hydrodynamics equations by the SOVA method [2]. At the stage of flight through the atmosphere, the equations are solved in a two-dimensional axisymmetric coordinate system associated with a moving body. When the body reaches the ground or decelerates in the atmosphere, the distributions of hydrodynamic and thermodynamic variables are used as input data for the impact in the three-dimensional coordinate system associated with the ground [3]. The propagation of shock waves in the atmosphere is simulated using a 3D code. To take into account vaporization of meteoroid fragments and fireball cooling by radiation we use two approximations of the radiative transfer equation: the approximation of radiation heat conduction with Rosseland free paths of photons for optically thick medium and the approximation for optically thin medium in which emitted energy is proportional to the Plank function [4]. The calculation of radiation fluxes on the ground at certain instants of time is carried out by solving the spectral equation of radiation transfer along rays crossing the region of heated air and vapor.

Results: We calculated pressure and wind velocity distributions near the Earth's surface after the impacts. Oblique (at 30° to horizon or less) impacts result in highly asymmetric distributions, whereas impacts at angles of 45° or larger produce more or less symmetric distributions. The total area of severe damage always increases with decreasing angle of impact. 300-m-diameter comets striking at 15°–30° to horizon generate strong devastating atmospheric shock waves over an area of ~1000 km^2, but do not produce any craters. For crater-forming impacts, the total area of extremely strong damage (and 100% mortality) is several orders of magnitude larger than the area of a corresponding impact crater including its continuous ejecta blanket.

The calculations of radiation fluxes on the Earth's surface show that luminous efficiency of superbolides is most sensitive to the entry angle and size and has a maximum for bodies with diameters of 10–30 m. The luminous efficiency of icy 30-m-diameter bodies entering the atmosphere at acute angles can reach 40%; the duration of a radiation impulse is ~2c. This duration is from ~ 1 minute for an impacting body of 300 m in size to ~ 10 minutes for a size of 3 km. The fraction of the kinetic energy of an impactor, which is converted into the energy of thermal radiation reaching the Earth's surface, can vary from ~ 0.5% to ~ 9%. After the impacts with a speed of 20 km/s at an angle of 45º, a fire can occur at a distance from the crater which is 700-1000 times larger than the diameter of a body, e.g., at a distance of up to 1000 km when the diameter of a body is one kilometer. The area of a region with molten soil can be quite extensive, and after the impact of a body with a diameter of 3 km it can stretch for ~500 km.

The impacts of comets and asteroids larger than ~50 m produce atmospheric plumes which eject impact products and dense cold air from the lower atmosphere to altitudes up to thousands of kilometers. As a result, at altitudes from 100 to several thousands of kilometers and distances up to several thousands of kilometers a disturbed region is formed, where the density of air is by several orders of magnitude greater than the normal one.

Our estimates of seismic effects show that the seismic efficiency of crater-forming impacts can be estimated as $(2–6)\times10^{-3}$, while the seismic efficiency of meteoric airbursts is $(1–5)\times10^{-5}$.

Analysis of the results of numerical simulations made it possible to obtain simplified approximations that describe the effects caused by a shock wave, overpressure and wind speed, thermal radiation on the surface for bodies entering the atmosphere with an arbitrary selected size, speed and angle of entry. Based on the developed scaling relations, a model of a calculator for assessments of effects of meteoric airbursts was implemented.

Conclusions: Atmospheric shock waves produce the most hazardous effects even in crater-forming events. Direct thermal radiation from a fireball and an impact plume poses a great danger to people, animals, plants, economic objects. The perturbations of the ionosphere can be significant, but their dangerous consequences need further study.

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References: [1] Collins G. S. et al. (2005) *Meteoritics & Planetary Science* 40:817–840. [2] Shuvalov V. V. (1999) *Shock Waves* 9:381–390. [3] Shuvalov V. V. et al. (2017) *Solar System Research* 51:44–58. [4] Shuvalov V. V. et al. (2017) *Planetary and Space Science* 147:38–47.